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FUEL CELLS

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TECHNICAL PAPER proposed for presentation at
Fifty-Eighth National Meeting of the American
Institute of Chemical Engineers
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1965

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ABSTRACT

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The flight of Gemini V marked the first demonstration of the use of fuel cells as spacecraft power systems. They have also been selected to power the NASA's Apollo and Biosatellite spacecraft and are prime candidates for use on the Air Force's Manned Orbiting Laboratory. A fuel cell may be considered to be an isothermal steady-state reactor in which the conversion of hydrogen and oxygen to water is accomplished. In order to maintain steady-state operation, heat and product removal techniques must be applied to the fuel cell. Three hydrogen-oxygen fuel cell systems are currently under development for aerospace applications. The three are described in terms of their basic operating parameters and construction features. The methods by which each system accomplishes the required heat- and mass-transfer operations are described.

Author

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The use of fuel cells for spacecraft power will become increasingly common in the future. The flight of the Gemini V was the first practical demonstration of their application as a primary spacecraft power system. In addition, they have already been selected to supply the main power for the Apollo spacecraft and for the Biosatellite. They are also being considered for the Air Force's Manned Orbital Laboratory. Undoubtedly other missions, both manned and unmanned, will follow. This paper reviews the current status of fuel cells for space missions. The major systems under development at the present time are described, with particular emphasis on the chemical engineering aspects of the systems.

In reviewing the systems which are currently being developed for spaceflight applications, it is necessary to keep in mind that these systems are designed to meet different types of requirements and restraints than would a system designed to operate on Earth. The economics of space flight place a premium upon weight reduction. Therefore, it becomes financially sound to use precious metal catalysts if the efficiency increase achieved leads to a lighter overall system. In a like manner, reduction in parasitic power requirements through the use of passive or self-operating system components is desirable since this upgrades the overall system efficiency. The space environment poses some unique problems to the fuel cell engineer, the most significant of which is zero gravity. This dictates that special attention be paid to gas-liquid separations which are required in a particular system design. Overriding these considerations is the requirement for high reliability, which is placed upon all components of a spacecraft. So strong is the need for high reliability, that simple, maintenance-free component designs may sometimes be chosen over a more complicated, but potentially lighter or more efficient device, for performing the same function. Thus, designs of spacecraft components reflect a compromise between the desire to use advanced concepts to achieve superior performance and the need to maintain a conservative viewpoint in order to ensure high reliability.

At the present time, NASA is supporting the development of three different hydrogen-oxygen fuel cell systems. The General Electric Company has developed an ion-exchange membrane fuel cell system, which is currently being used on the Gemini spacecraft. A smaller version of this power system will also be used to supply electrical energy for the Biosatellite. Pratt & Whitney Aircraft is developing a medium-temperature fuel cell powerplant for use on the command/service module portion of the Apollo spacecraft. In addition to these flight programs, the Allis-Chalmers Corporation is presently developing breadboard hardware which will be used to evaluate its fuel cell system for possible future flight applications.

The basic function of these three systems is identical, namely, the conversion of hydrogen and oxygen gases directly into electrical energy. Despite this similarity, each system differs physically and functionally from the others. The differences arise from the specific operating characteristics of the individual fuel cells which place different performance requirements upon the auxiliary components, which, together with the fuel cells, make up the complete power system.

From a chemical engineer's viewpoint, the fuel cell may be considered as a continuous isothermal reactor. As shown in figure 1, the fuel cell receives a continuous supply of fuel and oxidant. In order to maintain steady-state operation, the reaction product must be removed at the same rate at which it is formed and, depending on the specific type of cell involved, an exchange of heat with the surroundings must take place. This exchange may take the form of either heat rejection or absorption. In the case of fuel cells for spacecraft, the fuel is hydrogen gas, which is a highly efficient and energetic fuel when combined with pure oxygen as the oxidant. In order to maintain steady-state operating conditions within the reactor, the reaction product water is continuously removed. For a single cell operating at 0.8 volt and 100 percent current efficiency, the total hydrogen and oxygen consumption is 0.926 pound per kilowatt-hour. Since all material produced in the fuel cell must be removed, this figure is also equal to the water removal rate. Under these conditions, the heat which must be rejected from the fuel cell is equivalent to 2000 Btu per kilowatt-hour if the water leaves as saturated vapor, or 2990 Btu per kilowatt-hour if the water is exhausted as saturated liquid.

Table I compares the operating characteristics of the basic fuel cell reactors. It is interesting to note that for the operational parameters shown, temperature, pressure, and efficiency, the systems follow the same order, with General Electric ranking first, Allis-Chalmers second, and Pratt & Whitney third. The fixed weights of the basic power systems, exclusive of fuel and tankage, also follow the same order.

The differences in electrolyte composition and operating temperature for the various cells naturally result in significant variations in materials of construction. For instance, the General Electric cell, with its low operating temperature and acidic electrolyte material, tends to make liberal use of plastics and uses titanium metal for the few metallic parts that are present. Reinforced plastic is used for the cell frames as well as the hydrogen and coolant manifolds. The only metallic parts are the electrodes, current collector plates, and coolant tubes. The General Electric cell uses a solid plastic ion-exchange membrane as the electrolyte. This membrane, a sulfonated polystyrene resin, has the ability to conduct protons while excluding gas. The cell operates at temperatures of 75° to 90° F with gas supplied at approximately 22 pounds per square inch absolute. Thirty-two cells, each measuring 7 by 8 inches, are connected in series to form a stack. Three such stacks electrically connected in parallel are contained within a single canister. These are shown in figure 2. Each canister with its accessories is called a section and constitutes an independent power supply. A mockup of a complete section is shown in figure 3. The transparent end cap on the model shows the coolant and hydrogen manifold connections. The accessory package is mounted on the side. Two sections are used on the Gemini spacecraft. Each produces from 120 to 640 watts and has a short-time capability to supply 1050 watts. The installed efficiency of the Gemini system is 51 percent.

The Pratt & Whitney system which is being developed for the Apollo spacecraft uses a molten highly concentrated potassium hydroxide electrolyte. The 78 percent potassium hydroxide solution is heated to 400° to 425° F in the cell. The single cell is again the basic building block of the power system. Thirty-one series-connected cells are contained in a single power unit, called a module in the Apollo system. Figure 4 shows a module, consisting of a stack and its accessory package, being assembled. The Apollo spacecraft carries three modules, each of which delivers 563 to 1420 watts, with an emergency overload capability of 2295 watts. The reactant gases are supplied at 60 pounds per square inch absolute, and the installed efficiency of the system is 61 percent. In order to handle concentrated potassium hydroxide at over 400° F, Pratt & Whitney makes use of nickel as the major material of construction for their fuel cell. It is used in sintered powder form to make the electrodes and in solid form for the cell case. Teflon is used for gaskets between the cell halves.

Allis-Chalmers has the problem of handling a 35 percent potassium hydroxide solution at temperatures near 200° F. The electrolyte is retained within an asbestos matrix or blotter between the electrodes. In this case, the composition and temperature are sufficiently moderate so that the use of gold- or nickel-plated magnesium for the major structural components within the stack is possible. In order to minimize system weight, pairs of cells connected in parallel are arranged about common water-removal cavities. Thirty to thirty-three pairs are connected in series to form a stack. A nominal-2-kilowatt stack is shown in figure 5. Testing of breadboard power systems is being performed at both Allis-Chalmers and the NASA Manned Spacecraft Center.

The differences in electrolyte composition and operating temperature result in different approaches to temperature control and mode of water removal. The specific approaches presently used are described in the following paragraphs. Figure 6 is a schematic representation of the fuel cell system developed for the Gemini spacecraft. The Gemini fuel cell uses a circulating coolant, normally a glycol-water mixture, which is pumped directly through tubes attached to the oxygen side of the fuel cell as the means for temperature control. The heated coolant is used to preheat incoming gasses. The remainder of the heat is rejected through a radiator. In addition to removing waste heat, the coolant also serves as the driving force for the water removal step. The process is illustrated in figure 7. Water is produced within the fuel cell at a vapor pressure approximately equal to that of pure water at the cell operating temperature. The coolant tubes, which are attached to the oxygen current collector plate, cause a temperature gradient to exist between the surface of the electrolyte and the oxygen collector plate. As can be seen from figure 7, woven cloth wicks are placed within channels preformed into the oxygen current collector plate. The water which is vaporized at the oxygen electrode condenses on the wicks because of the temperature gradient imposed by the coolant. The capillary action of the wicks serves as a passive means for transporting water from the fuel cell to a collection vessel. Although the operating current density and efficiency of this cell are somewhat lower than those of the other cells being developed, the favorable construction characteristics lead to a lightweight system. The almost entirely passive heat and mass transfer system allows very low parasitic power consumptions ranging from 3 to 4 percent of the gross power output. The Gemini system has already passed flight vehicle qualification tests and with the flight of Gemini V became the first fuel cell system to be orbited aboard a spacecraft.

The system which Pratt & Whitney is developing for the Apollo spacecraft has already undergone its preliminary flight qualification testing. The fuel cell uses a free electrolyte which is held between the electrodes by the dual-porosity structure of the electrodes. The heat- and mass-transfer operations are performed at the hydrogen electrode, as shown in figure 8. A quantity of hydrogen gas in excess of that required for the electrochemical reaction is constantly circulated past the hydrogen electrode. Water evaporates from the electrode surface into the gas stream. The rate of water removal is controlled by the relative saturation of the incoming gas. Heat is likewise removed in the hydrogen stream by controlling the inlet temperature. The overall system schematic is shown in figure 9. The moist, hot hydrogen undergoes a two-step temperature reduction to condense the amount of water required. The stream is partially cooled in the fuel regenerator and then passes through a water condenser to complete the condensation. The two-phase stream then passes through a combined pump-separator unit. The rotating separator creates an artificial gravitational field which allows separation of liquid water from the gas. The hydrogen gas is then returned to the fuel cell. The power consumption of the hydrogen pump and water separator units tends to make the parasitic power requirement for this system somewhat high, generally near 10 percent. In addition, the fixed weight of the fuel cell stack tends to be higher than that of the other two systems discussed because of the extensive use of nickel as a material of construction. However, the high efficiency of this fuel cell as compared to the others makes it attractive where relatively large kilowatt-hour outputs are required.

The Allis-Chalmers fuel cell system is the only one described in this paper in which the heat- and mass-transfer operations are entirely separate and independent. The cell is maintained at a constant temperature by circulating helium gas as a coolant over the cell stack. Heat is conducted from within the individual cells to the outer surface through the magnesium structural material. The water-removal procedure is shown schematically in figure 10. Hydrogen gas is fed to the back side of the hydrogen electrode between the electrode and a second asbestos pad containing a potassium hydroxide solution that is more concentrated than that within the electrolyte pad. For example, if the cell electrolyte concentration is 35 percent, the solution in the water-removal pad may be 40 percent potassium hydroxide. The difference in concentrations causes a water vapor pressure gradient to exist between the electrolyte matrix and the water-removal matrix. This vapor pressure gradient acts as the driving force for water removal. Water is automatically transferred from the electrolyte membrane to the water-removal matrix. In order to prevent the two pads from reaching a concentration equilibrium, the rear side of the water-removal matrix is exposed to vacuum. The pressure in the chamber is varied in order to maintain the desired electrolyte concentration within the water-removal matrix itself, and therefore to control the vapor pressure gradient. This is accomplished by means of a vacuum regulator valve in the water-removal stream. The main parasitic power consumers in the system are the helium circulating fans within the module canister. For a complete powerplant, parasitic power is estimated to be about 6 percent of the gross output. The system can be designed to accomplish water recovery by placing a condenser in the exhaust stream from the water-removal cavity. As presently conceived, a circulating coolant controls the temperature of an asbestos matrix which acts as the condensing surface. The capillary forces of the asbestos transfer the water to a storage vessel in the same manner as the wicks in the General Electric system. The Allis-Chalmers system is currently undergoing performance tests in breadboard form at the NASA Manned Spacecraft Center in Houston, Texas. It is anticipated that this system will receive serious consideration for future flight missions.

Thus, it can be seen that primary hydrogen-oxygen fuel cell systems may be viewed as process variations on a single chemical reaction. The reactor designs and operating conditions differ. As a result, the heat- and mass-transfer modes are designed to be compatible with the specific set of operating conditions involved. However, in every case, the net result is the same, namely, the direct conversion of hydrogen and oxygen to water and electrical energy. While background research must be conducted by electrochemists and chemists, the engineering development associated with converting a single fuel cell into a working power system is a job which seems to be uniquely suited to the training and interests of the chemical engineer. While three systems are currently in an advanced development state for spaceflight applications, there is still room for overall improvement, particularly in the areas of weight reduction, parasitic power reduction, and reliability. Therefore, the fuel cell systems of the future would be expected to result from finding simpler, more reliable, and more efficient means for performing the heat- and mass-transfer operations required to operate the fuel cell as an isothermal steady-state reactor.

TABLE I. - FUEL CELL OPERATING CHARACTERISTICS

Source	Electrolyte	Operating temperature, °F	Reactant pressure, psia	Installed efficiency, percent
General Electric	Ion-exchange membrane	75 to 90	22	51
Pratt & Whitney	78 Percent potassium hydroxide	400 to 425	60	61
Allis-Chalmers	35 Percent potassium hydroxide	190 to 200	37	[a]57

[a]Estimated

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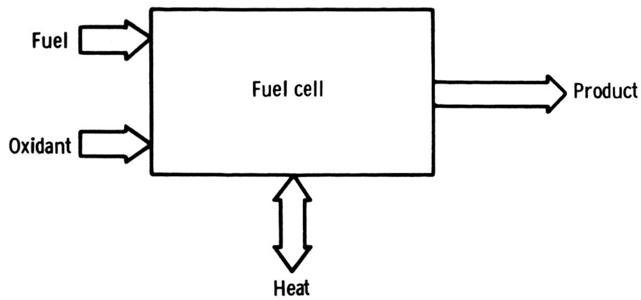

Figure 1. - Fuel cell flow diagram.

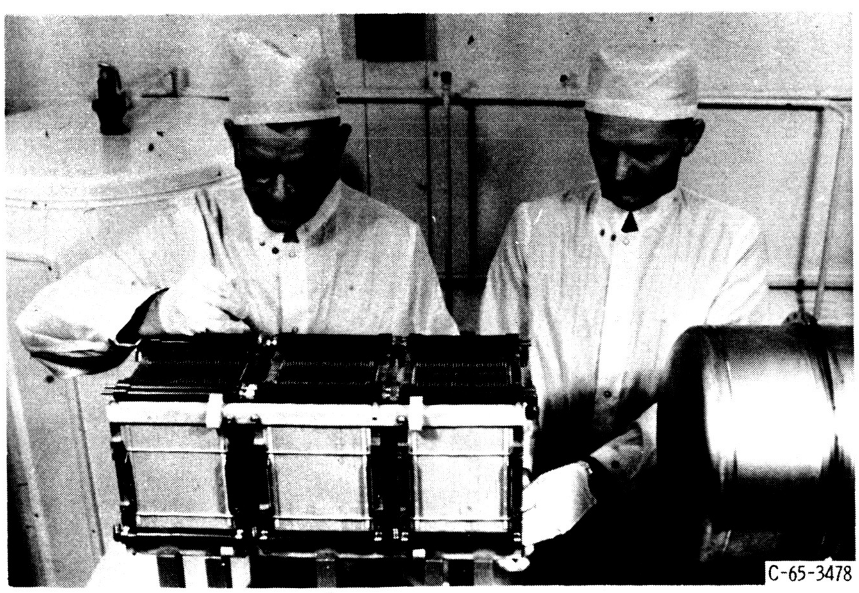

Figure 2. - Gemini fuel cell stack assembly.

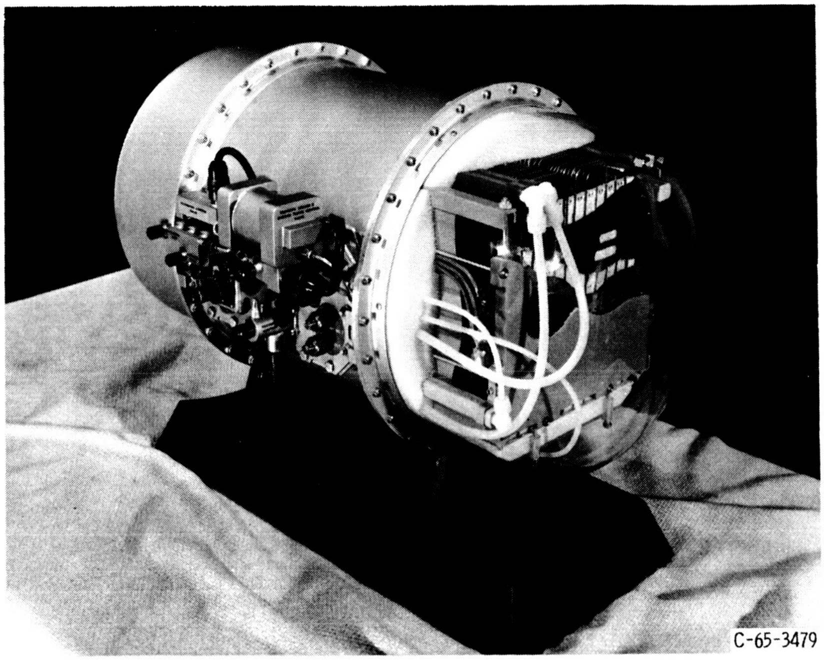

Figure 3. - Gemini section model.

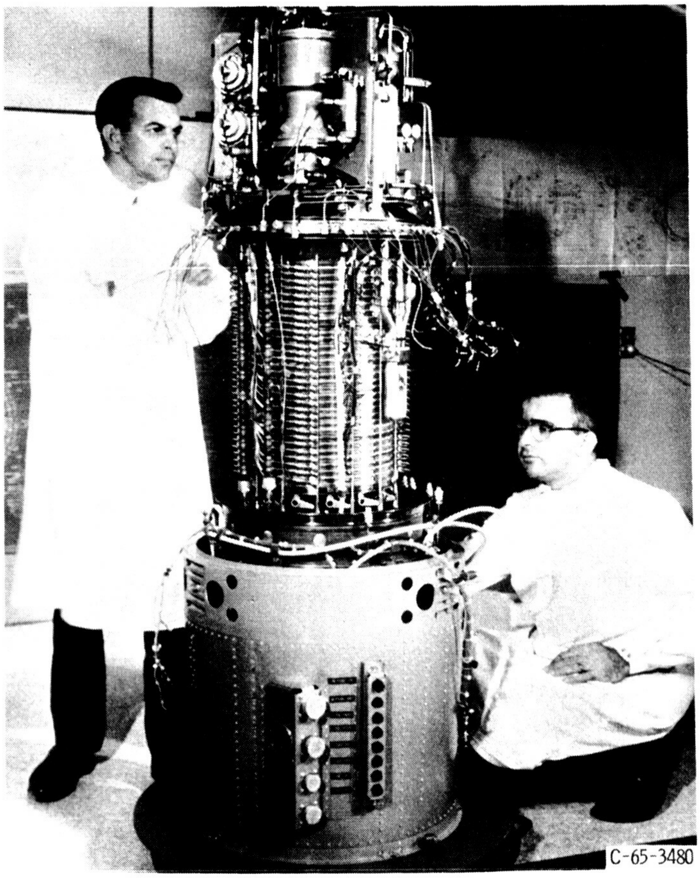

Figure 4. - Apollo fuel cell assembly.

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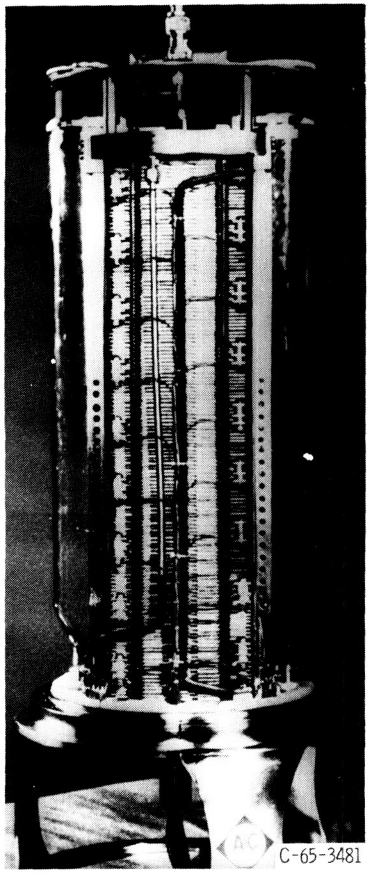

Figure 5. - Allis-Chalmers fuel cell stack.

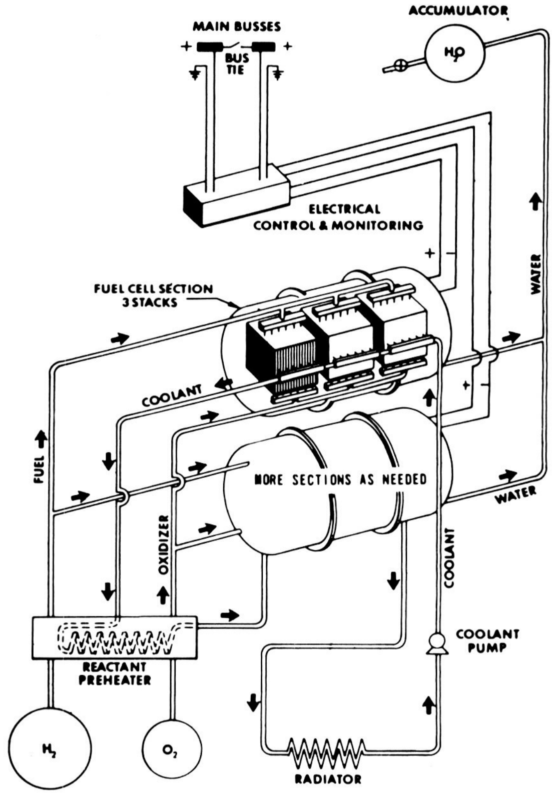

Figure 6. - Schematic drawing of Gemini fuel cell system.

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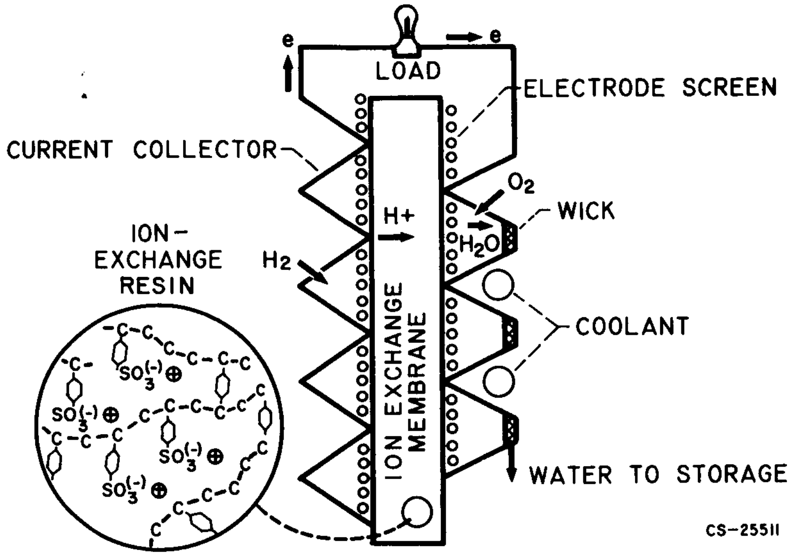

Figure 7. - Ion-exchange membrane fuel cell for space application.

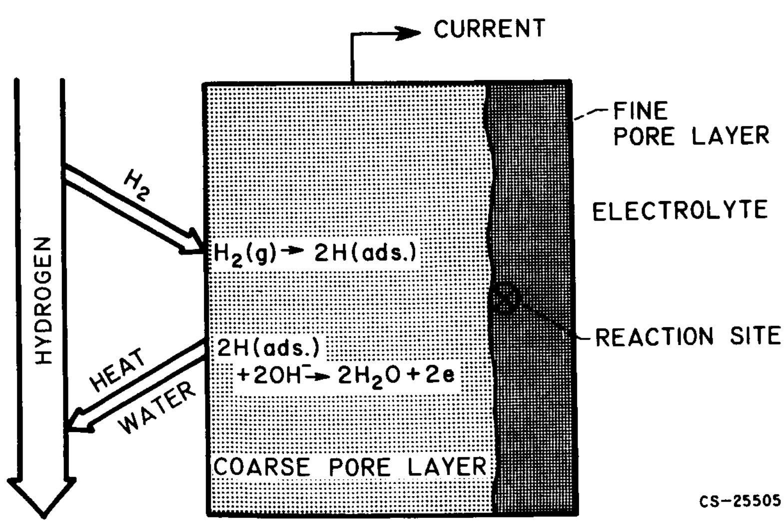

Figure 8. - Hydrogen electrode processes in Bacon-type fuel cell.

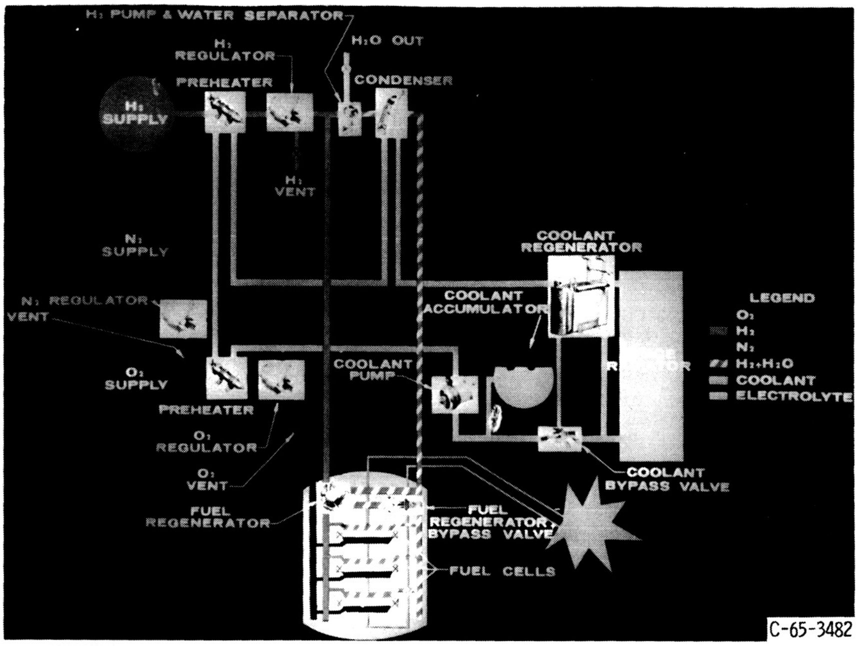

Figure 9. - Schematic drawing of Apollo fuel cell system.

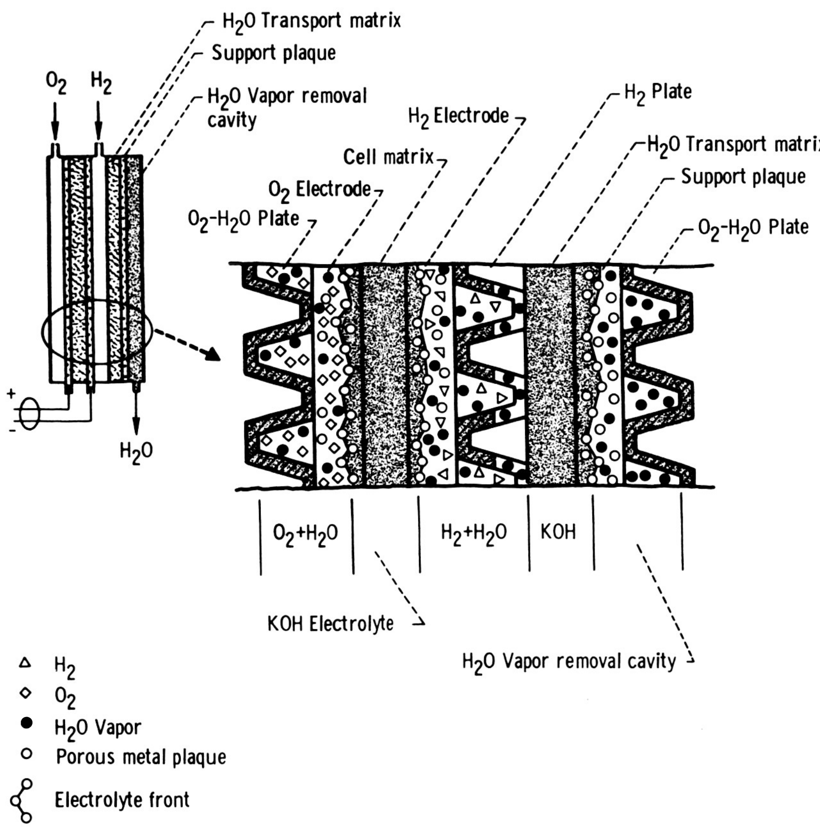

Figure 10. - Static vapor pressure control water-removal system.